TÉCNICO LISBOA

No Routes Wasted for Waste Collection: Exploring real-time information through ML techniques to improve waste collection

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WSMARTROUTE

OPERATION RESEARCH MEETS MACHINE LEARNING
how to get the most of both worlds to achieve excellent Decision Support System

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Introduction

University

TÉCNICO LISBOA

Research Centres :

CEG-IST -> Operations & Logistics; Routing; Optimization

INESC-ID -> Machine Learning

- How to treat the data available?
- How to improve the collection operation based on that data?

Technological Company

evox Inspiring Innovation

Ultrasonic sensors

360 WASTE

Dashboard

18 sensorized bins

Municipality

CÂMARA MUNICIPAL CASTELO BRANCO

Objective

- Define smart collection routes that maximize operational profit while avoiding bins' overflow using real-time data on the bins' fill-level (transmitted by ultrasonic sensors placed inside the bins)

  - Adequate treatment of real time data
  - Development of optimization models that account for these real time data

How to treat the data available?

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- 18 sensorized bins since September 2017;
- Data is transmitted whenever a significative variation occurs at the bins' fill-level: Several transmissions per day.

Descrição	Actual Volume	%/day	Evolution	Last Reading
48843 Contentor 607 - Exterior 800 litros - Polietileno - Resíduos Sólidos Urbanos	68%	39		19/06/2018 20:35
15415 Contentor 611 - Exterior 1000 litros - Polietileno - Resíduos Sólidos Urbanos	100%	39		19/06/2018 18:38
49619 Contentor 603 - Exterior 800 litros - Polietileno - Resíduos Sólidos Urbanos	48%	29		19/06/2018 15:16
52910 Contentor 606 - Exterior 800 litros - Polietileno - Resíduos Sólidos Urbanos	31%	16		19/06/2018 11:06
50419 Subterrâneo 3 - 616 - Exterior 1000 litros - Polietileno - Resíduos Sólidos Urbanos	51%	23		19/06/2018 08:29

Source: Extracted from 360Waste Platform (www.360waste.pt)

How to treat the data available?

Day 16/06 Day 17/06 Day 18/06 Day 19/06

Descrição	Volume Atual	%/dia	Evolução	Última Leitura
48843 Contentor 607 - Exterior 800 litros - Polietileno - Resíduos Sólidos Urbanos	68%	39		19/06/2018 20:35
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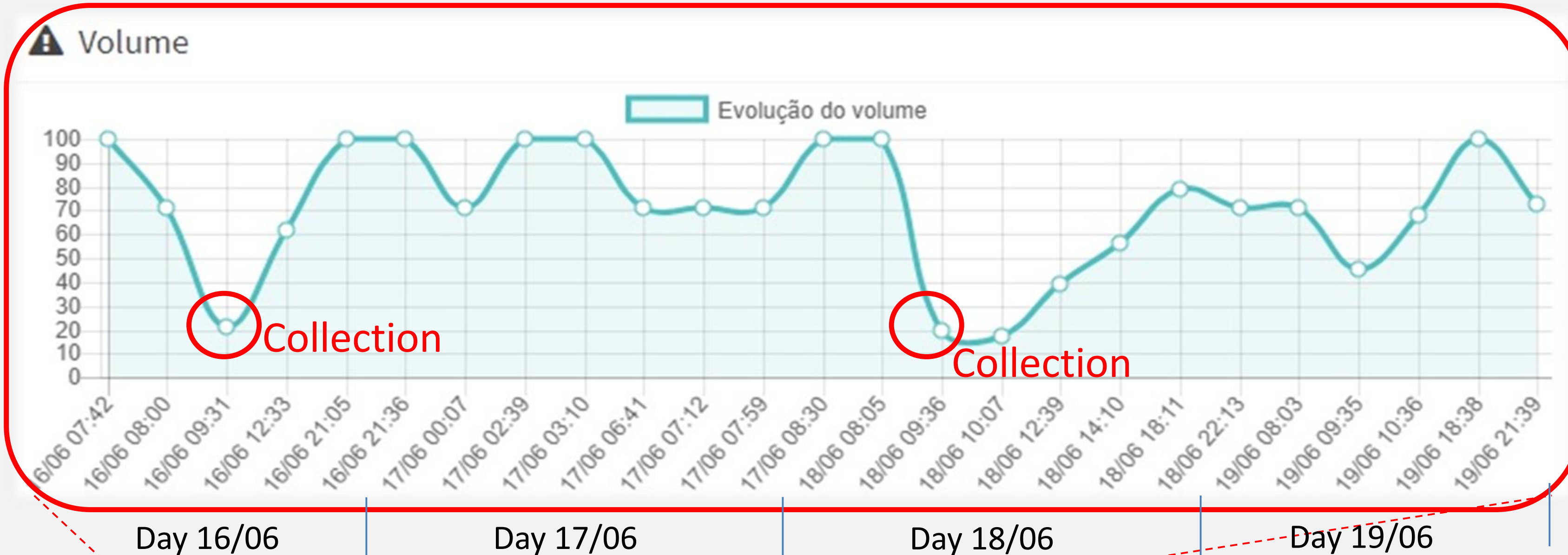

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How to treat the data available?

Day 16/06 | Day 17/06 | Day 18/06 | Day 19/06

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IMPORTANT: adequate treatment of the available data.

How to treat the data available?

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Machine Learning

Sensors:

- Sensors give a "noisy" measure of the volume as the height inside of the container is not uniform;
- Volume can reduce when heavier objects are inserted.

Container:

- We measure volume but the total volume changes stochastically with time; and **we want to avoid containers' overflowing.**

Predict when a container will be completely full based on noisy sensors

How?

Hidden Markov Models (HMM)

Probabilities of becoming full are learnt from the observations

How to treat the data available?

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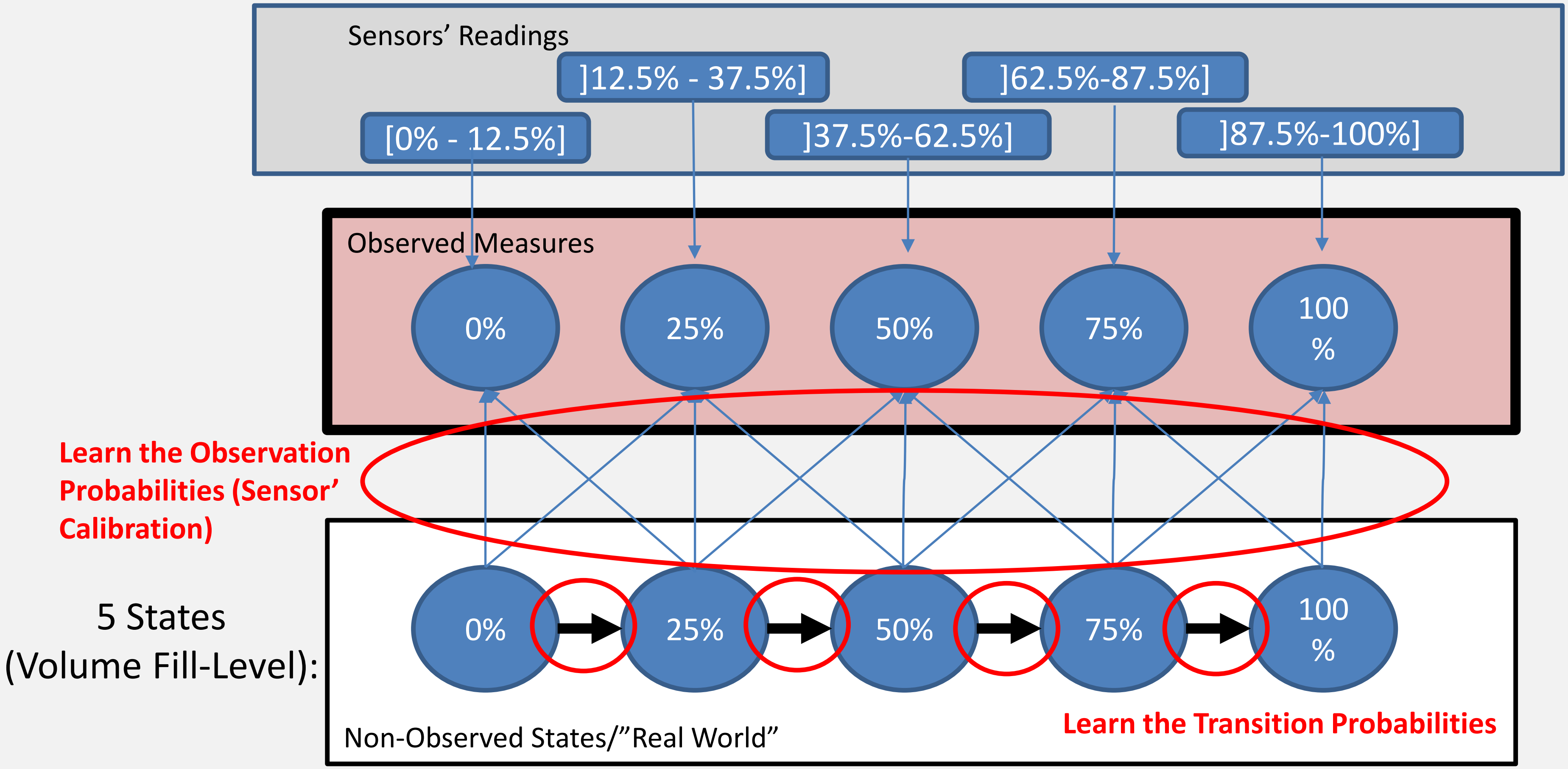
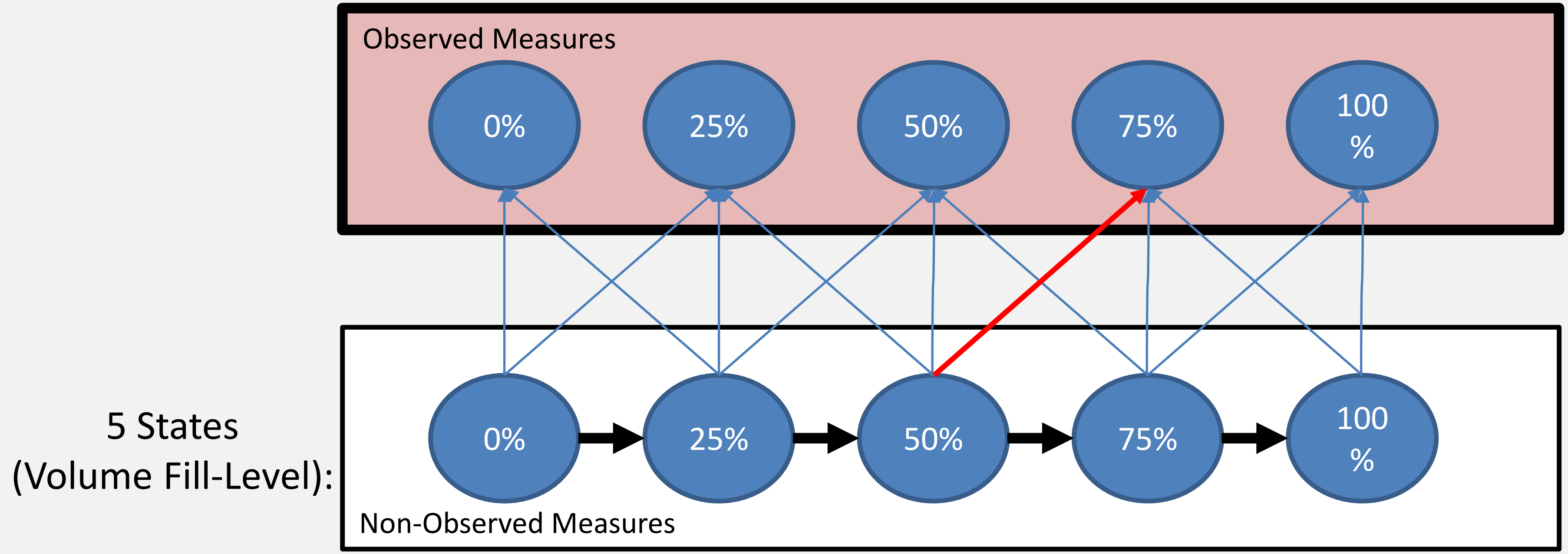
Hidden Markov Models (HMM)



How to treat the data available?

Hidden Markov Models (HMM)



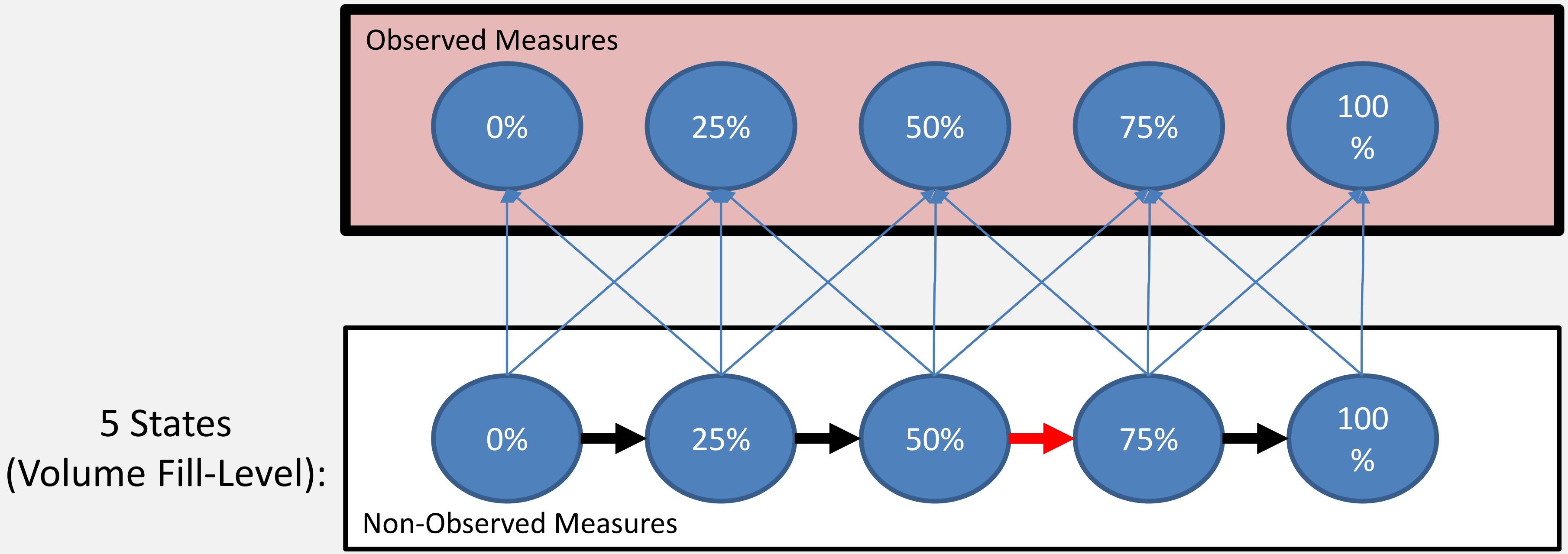
Probability of Observation

P(Observation|State)

e.g. P(Observation = 75% | State =50%) =0.1 -> Probability of 10% of measuring 75% filling when in reality it is just 50%

How to treat the data available?

Hidden Markov Models (HMM)



Probability of Transition

$P(State_{t+1}|State_t)$

e.g. $P(State_{t+1}=75\%|State_t=50\%) = 0.8$ -> Probability of 80% to change from state 50% to stage 75% in the next day

How to treat the data available?

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Hidden Markov Models (HMM)

e.g.

Bin 601

Probability of each state at each day in the future, given the observation measure $p(x_{t+d}|o_t)$

Observed Measure: 0%

	States				
DAYS	**0%**	**25%**	**50%**	**75%**	**100%**
0	0.875	0.125	0	0	0
1	0.08643	0.237477	0.296044	0.22099	0.159059
2	0.008537	0.045695	0.116409	0.187722	0.641637
3	0.000843	0.00671	0.02583	0.064063	0.902553
4	8.33E-05	0.00088	0.004532	0.015174	0.97933
5	8.23E-06	0.000108	0.000699	0.002948	0.996237
6	8.13E-07	1.28E-05	9.94E-05	0.000505	0.999381
7	8.03E-08	1.48E-06	1.34E-05	7.95E-05	0.999906

Observed Measure: 25%

	States				
DAYS	**0%**	**25%**	**50%**	**75%**	**100%**
0	0.2	0.7	0.1	0	0
1	0.019756	0.120603	0.250297	0.27873	0.330614
2	0.001951	0.016996	0.061712	0.132441	0.7869
3	0.000193	0.002181	0.011057	0.034494	0.952075
4	1.90E-05	0.000265	0.001711	0.00695	0.991054
5	1.88E-06	3.11E-05	0.000243	0.001211	0.998513
6	1.86E-07	3.55E-06	3.26E-05	0.000192	0.999772
7	1.84E-08	3.99E-07	4.19E-06	2.84E-05	0.999967

Observed Measure: 50%

	States				
DAYS	**0%**	**25%**	**50%**	**75%**	**100%**
0	0	0.111111	0.777778	0.111111	0
1	0	0.010975	0.105415	0.244599	0.63901
2	0	0.001084	0.013236	0.054593	0.931086
3	0	0.000107	0.001586	0.009125	0.989181
4	0	1.06E-05	0.000184	0.001342	0.998463
5	0	1.04E-06	2.09E-05	0.000183	0.999795
6	0	1.03E-07	2.34E-06	2.38E-05	0.999974
7	0	1.02E-08	2.57E-07	2.98E-06	0.999997

Observed Measure:75%

	States				
DAYS	**0%**	**25%**	**50%**	**75%**	**100%**
0	0	0	0.111111	0.777778	0.111111
1	0	0	0.010975	0.105415	0.88361
2	0	0	0.001084	0.013236	0.985679
3	0	0	0.000107	0.001586	0.998307
4	0	0	1.06E-05	0.000184	0.999805
5	0	0	1.04E-06	2.09E-05	0.999978
6	0	0	1.03E-07	2.34E-06	0.999998
7	0	0	1.02E-08	2.57E-07	1

Observed Measure: 100%

	States				
DAYS	**0%**	**25%**	**50%**	**75%**	**100%**
0	0	0	0	0.125	0.875
1	0	0	0	0.012347	0.987653
2	0	0	0	0.00122	0.99878
3	0	0	0	0.00012	0.99988
4	0	0	0	1.19E-05	0.999988
5	0	0	0	1.18E-06	0.999999
6	0	0	0	1.16E-07	1
7	0	0	0	1.15E-08	1

How to treat the data available?

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Hidden Markov Models (HMM)

e.g.

Bin 601

Probability of each state at each day in the future, given the observation measure $p(x_{t+d}|o_t)$

Observed Measure: 25%

	States				
DAY	**0%**	**25%**	**50%**	**75%**	**100%**
0	0.2	0.7	0.1	0	0
1	0.019756	0.120603	0.250297	0.27873	0.330614
2	0.001951	0.016996	0.061712	0.132441	0.7869
3	0.000193	0.002181	0.011057	0.034494	0.952075
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5	1.88E-06	3.11E-05	0.000243	0.001211	0.998513
6	1.86E-07	3.55E-06	3.26E-05	0.000192	0.999772
7	1.84E-08	3.99E-07	4.19E-06	2.84E-05	0.999967

If the observed measure is 25%, there is a probability of 70% of the actual state to be 25%, 10% of the actual state to be 50% and 20% of the actual state to be 0%

How to treat the data available?

EWG POR
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Hidden Markov Models (HMM)

e.g.

Bin 601

Probability of the state at each day in the future given the observation measure $p(x_{t+d}|o_t)$

Observed Measure: 25%

	States				
DAY	**0%**	**25%**	**50%**	**75%**	**100%**
0	0.2	0.7	0.1	0	0
1	0.019756	0.120603	0.250297	0.27873	0.330614
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7	1.84E-08	3.99E-07	4.19E-06	2.84E-05	0.999967

If the observed measure is 25%, there is a probability of 12% of staying in that state in the next day, 25% of changing to the state 50%, 28% of changing to state 75% and 33% of becoming full in the next day

How to treat the data available?

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Hidden Markov Models (HMM)

e.g.

Bin 601

	Initial Morning Stock
2/Apr	62%

Sensors' information

Observed Measure
50%

If the bin is 50% full today, in how many days it will be completely full (100%)?

Probability Matrix from HMM

	Observed Measure: 50%				
	States				
DAYS	0%	25%	50%	75%	100%
0	0	0.111111	0.777778	0.111111	0
1	0	0.010975	0.105415	0.244599	0.63901
2	0	0.001084	0.013236	0.054593	0.931086
3	0	0.000107	0.001586	0.009125	0.989181
4	0	1.06E-05	0.000184	0.001342	0.998463
5	0	1.04E-06	2.09E-05	0.000183	0.999795
6	0	1.03E-07	2.34E-06	2.38E-05	0.999974
7	0	1.02E-08	2.57E-07	2.98E-06	0.999997

Bin 601 will be completely full (100%) after 2 days, with 93.1% of probability

Bin 601 will be completely full (100%) after 3 days, with 98.9% of probability

How to treat the data available?

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Hidden Markov Models (HMM)

e.g.

Bin 601

	Initial Morning Stock
2/Apr	62%

Sensors' information

Observed Measure
50%

Probability Matrix from HMM

	50%				
	States				
DAYS	0%	25%	50%	75%	100%
0	0	0.111111	0.777778	0.111111	0
1	0	0.010975	0.105415	0.244599	0.63901
2	0	0.001084	0.013236	0.054593	0.931086
3	0	0.000107	0.001586	0.009125	0.989181
4	0	1.06E-05	0.000184	0.001342	0.998463
5	0	1.04E-06	2.09E-05	0.000183	0.999795
6	0	1.03E-07	2.34E-06	2.38E-05	0.999974
7	0	1.02E-08	2.57E-07	2.98E-06	0.999997

Daily Accumulation Rate = (1 – 0.5) / 2 days 25%/day

Daily Accumulation Rate = (1 – 0.5) / 3 days 17%/day

Need to define a Confidence Level Threshold **95%**

Bin 601 will be completely full after 2 days, with 93.1% of probability

Bin 601 will be completely full after 3 days, with 98.9% of probability

How to improve the collection operation based on that data?

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Smart Waste Collection Routing Problem *(Ramos et al. 2018)*

Use of **real-time information** on the bins' fill-level (transmitted by volumetric sensors placed inside the bins) to define **smart collection routes** that **maximize operational profit:**

Max **PROFIT** = **revenues** obtained from the recyclable waste collected - **transportation costs** of collecting that waste

Maximize the amount of waste collected while minimizing distance travelled

How to improve the collection operation based on that data?

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Smart Waste Collection Routing Problem *(Ramos et al. 2018)*

Decision: To select the **waste bins to be visited** (if any) and the **optimal visiting sequence** in each ***day t*** for each ***vehicle k***, which will **maximize the profit** while satisfying the vehicles' capacity, the bins' capacity and a service level (measured by the number of overflowing bins).

How to improve the collection operation based on that data?

Decision: To select the **waste bins to be visited** (if any) and the **optimal visiting sequence** in each ***day t*** for each ***vehicle k***, which will **maximize the profit** while satisfying the vehicles' fixed capacity, the bins' capacity and a service level.

VRP with Profit (VRPP)[1] :
Maximize Profit for One Day

VRPP Model is solved every day *t*, in the morning, after receiving sensors' data on the bins' fill-level.

Problem: "Blind" to future events

[1](Ramos et al. 2018)

Inventory Routing Problem (IRP):
Maximize Profit for a Time Horizon

Static IRP

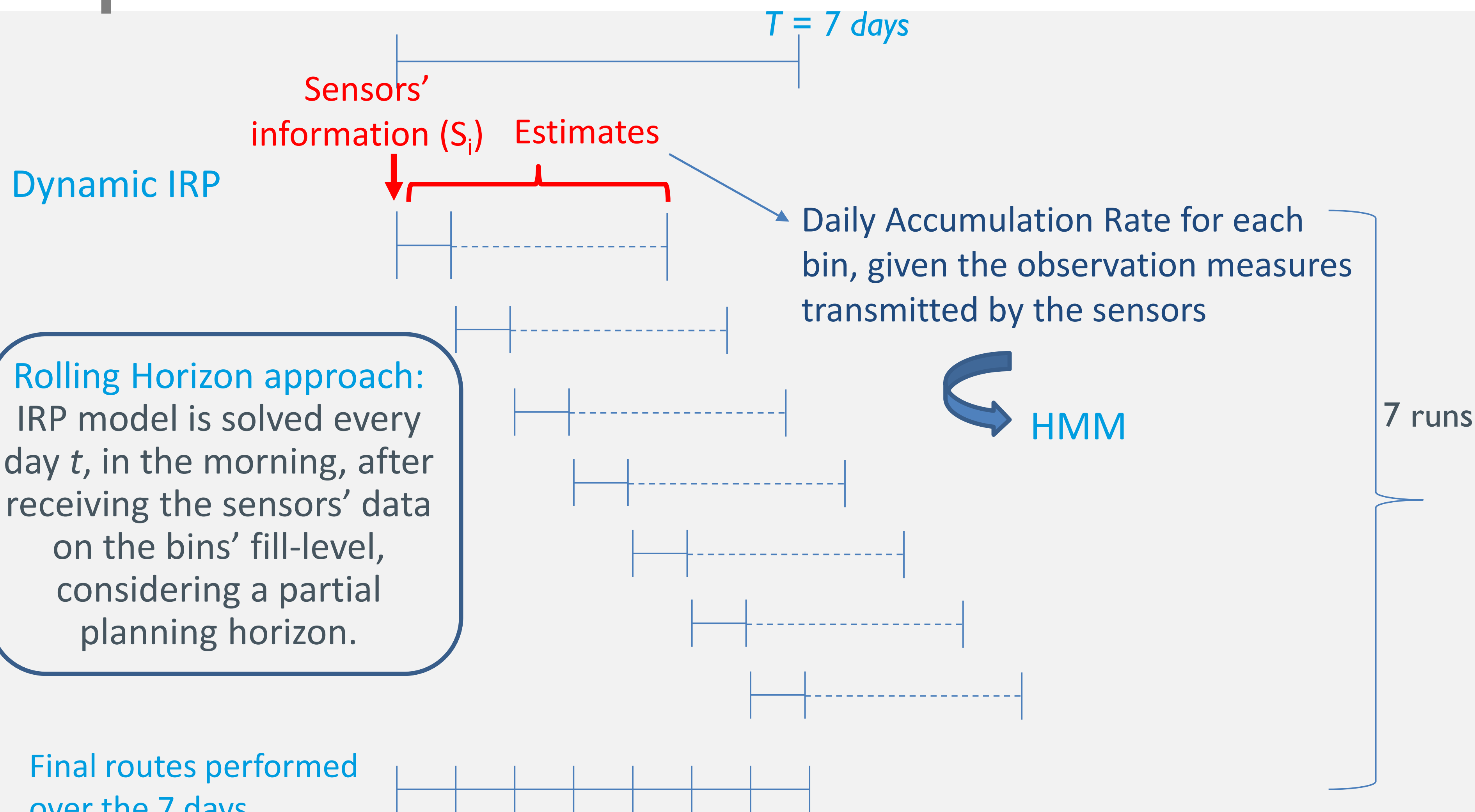
IRP model is solved at day t=1, in the morning, after receiving sensors' data, considering the entire planning horizon (e.g., 7 days).

Problem: Considers real-time data only for the first day (deals with estimates for the days ahead).

Dynamic IRP

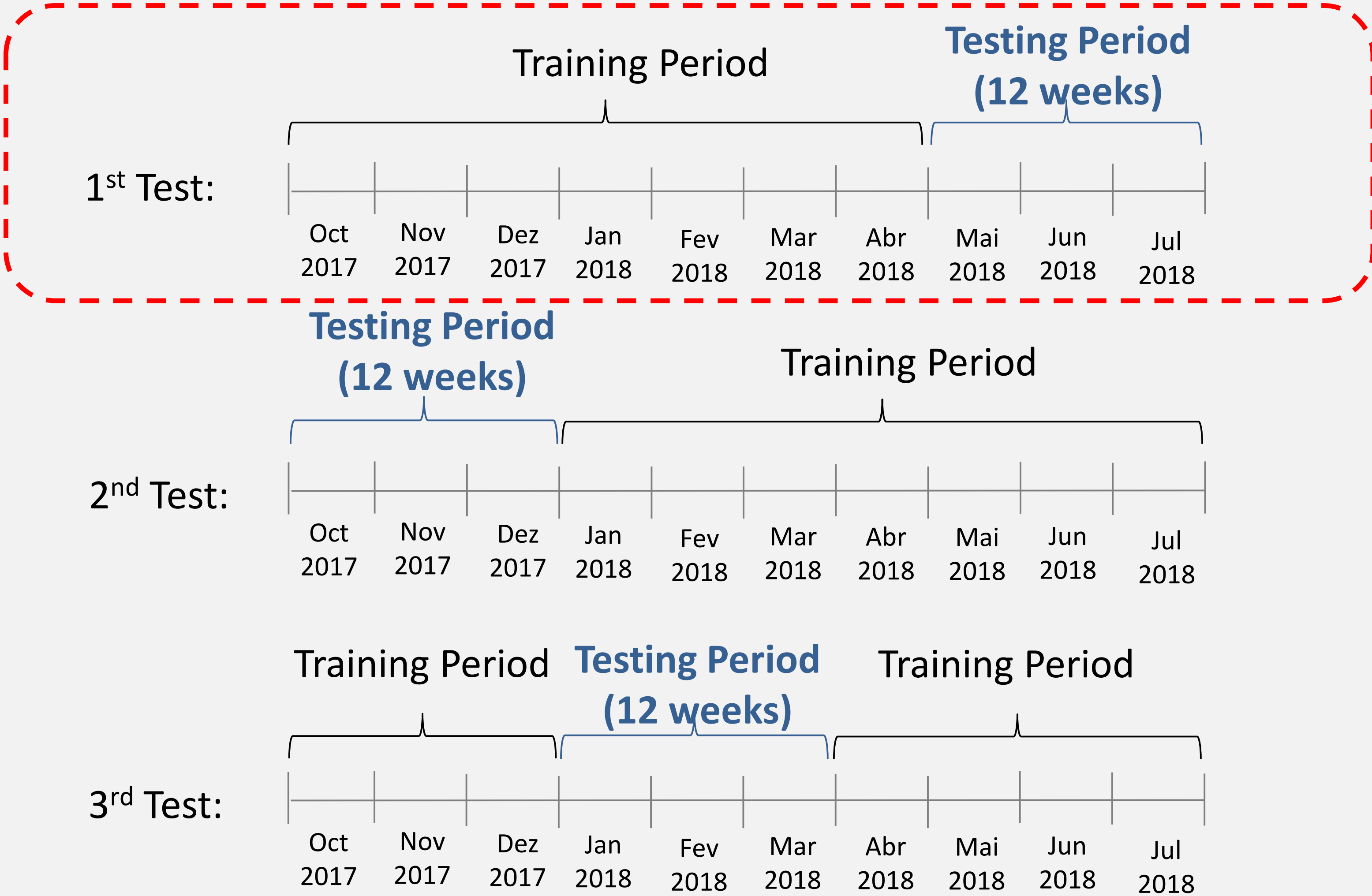
Considers a continuous data updating in the model.

How to improve the collection operation based on that data?



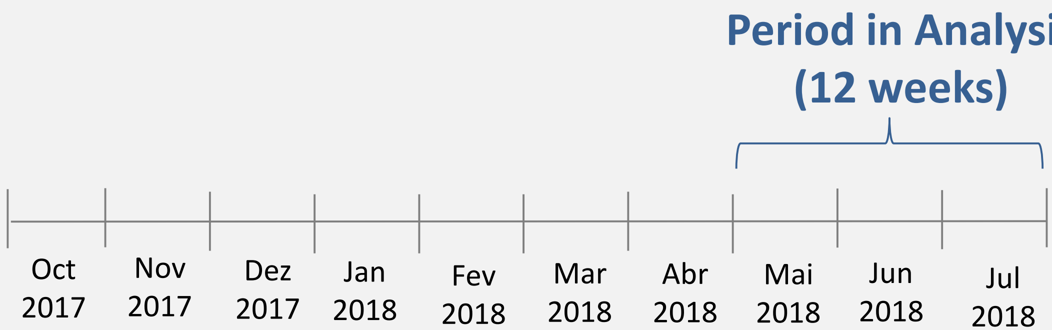
Rolling Horizon approach: IRP model is solved every day *t*, in the morning, after receiving the sensors' data on the bins' fill-level, considering a partial planning horizon.

Testing Set



Training Period
Testing Period (12 weeks)
1st Test:
Oct 2017
Nov 2017
Dez 2017
Jan 2018
Fev 2018
Mar 2018
Abr 2018
Mai 2018
Jun 2018
Jul 2018
Testing Period (12 weeks)
Training Period
2nd Test:
Oct 2017
Nov 2017
Dez 2017
Jan 2018
Fev 2018
Mar 2018
Abr 2018
Mai 2018
Jun 2018
Jul 2018
Training Period
Testing Period (12 weeks)
Training Period
3rd Test:
Oct 2017
Nov 2017
Dez 2017
Jan 2018
Fev 2018
Mar 2018
Abr 2018
Mai 2018
Jun 2018
Jul 2018

Results – Current Situation



- All 18 bins are collected every Monday, Thursday and Saturday, regardless its fill-level

KPI	TOTAL (12 weeks)	AVERAGE (week)
Weight (kg)	34 403	2 867
Distance (km)	3 584	299
Attended bins	648	54
Full bins (87,5%<S_i<100%)	0	0
Overflowing bins (S_i>100%)	235	20
Ratio (kg/km)	9.6	9.6

37% of the waste bins are overflowing

Poor Service Level

High Efficiency

Results – Dynamic IRP w/ HMM

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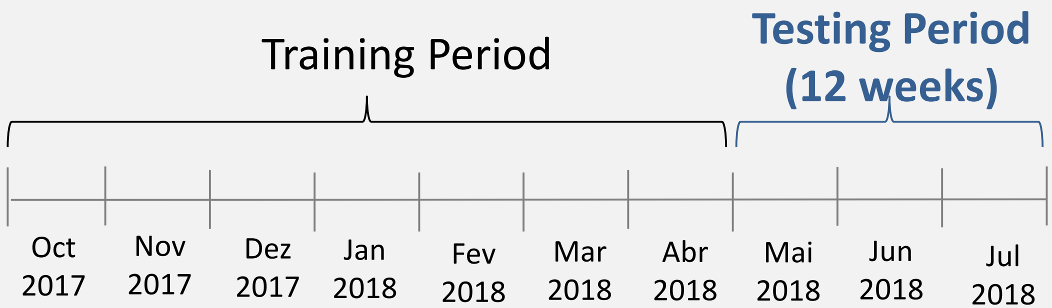
1st Test:



- The expected daily accumulation rate computed through the probability matrix from the HMM feeds the Dynamic IRP model

KPI	TOTAL (12 weeks)	AVERAGE (week)
Weight (kg)	38 753	3 229
Distance (km)	3 829	319
Attended bins	468	39
Full bins (87,5%<S_i<100%)	206	17
Overflowing bins ($S_i \geq$100%)	69	6
Ratio (kg/km)	10.1	10.1

15% of the waste bins are overflowing

Better Service Level

Higher Efficiency

Results – Dynamic IRP w/ HMM

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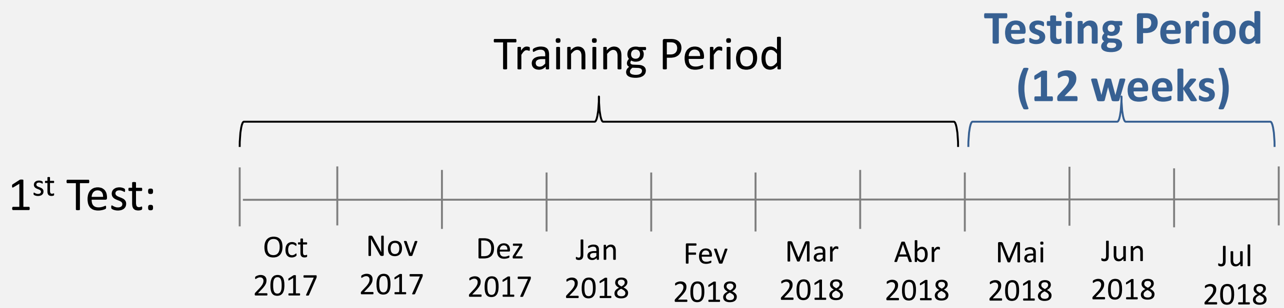
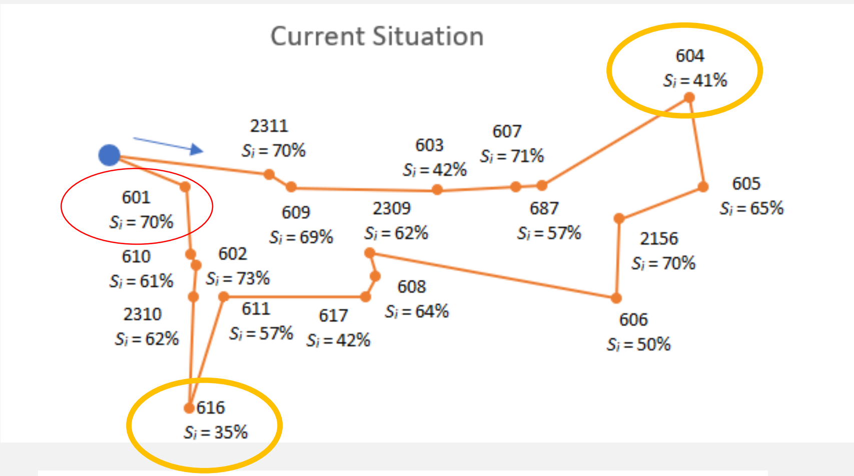


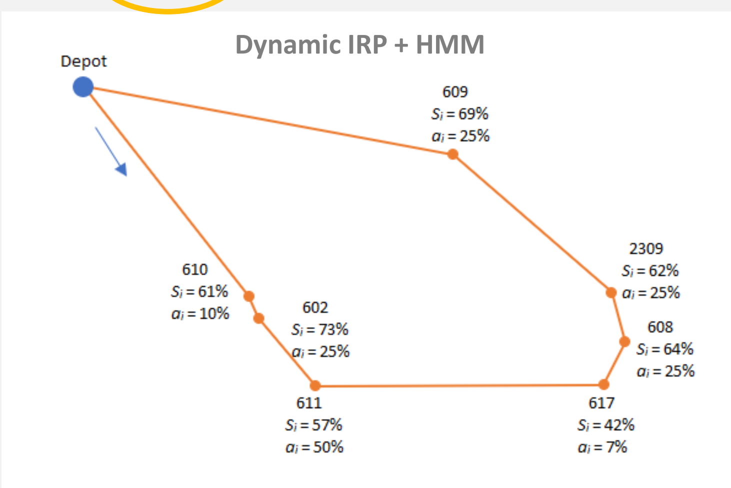
June – 1st week								
KPI	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total
Weight (kg)	578.54	392.92	0.00	493.74	530.22	241.57	562.76	2799.75
Distance (km)	57.23	47.88	0.00	64.53	57.23	47.31	57.23	331.41
Attended bins	7	5	0	5	6	3	7	33
Full bins (87.5%<Si<100%)	4	2	1	2	3	1	2	15
Overflowing bins (Si>100%)	0	0	0	1	0	0	0	1
Ratio (kg/km)	10.11	8.21	0.00	7.65	9.26	5.11	9.83	8.45

July – 3rd week								
KPI	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total
Weight (kg)	461.69	1651.55	26.62	11.09	1469.88	150.37	1061.7	4832.9
Distance (km)	37.53	82.93	20.84	8.30	98.79	21.59	63.1	333.1
Attended bins	7	17	1	1	16	3	14	59
Full bins (87.5%<Si<100%)	0	0	0	0	4	0	2	6
Overflowing bins (Si>100%)	0	7	0	0	3	0	0	10
Ratio (kg/km)	12.30	19.92	1.28	1.34	14.88	6.96	16.8	14.5

Results – Routes

e.g. July – 3rd Week, Day 1 (16/July)





e.g.

Bin 601

	Sensors' Reading (8 am)	HMM Daily Accumulation Rate	Actual Daily Accumulation Rate
16/Jul	70%	25%	65%

The IRP model chooses not to collect bin 601 at day 1 (where 70% of volume would be collected); it schedules bin 601 to day 2 (where 95% of volume would be collected)

But… Actual Accumulation Rate for bin 601 on day 16/Jul = 65%

Overflowing bin → 17/Jul = Sensors' Reading = 135% (70%+65%)

Conclusions

KPIs	Current Situation	Dynamic IRP + HMM	
Total weight (kg)	34 403	38 753	+ 13%
Total distance (km)	3 584	3 829	+ 6%
Total attended bins	648	468	- 28%
Total overflowing bins (Si≥100%)	235	69	- 71%
Ratio (kg/km)	9.6	10.1	+ 5%

- **Current Situation -> Efficient (high kg/km ratio), but… 235 overflowing bins!**

  3 routes/week

- **Dynamic IRP + HMM -> Reduces the number of overflowing bins in 71% (69 vs. 235) and increases the efficiency in 5% (10.1 kg/km vs. 9.6 kg/km).**

  5.7 routes/week (average)

Further Work

- **Data Treatment**

  Investing more time on Machine Learning techniques to treat properly the sensors' data

  - Increase the number of states in the HMM?
  - Test different confidence levels
  - Learning the Daily Accumulation Rates (using AutoRegressive models like ARX or ARMA) instead of learning the probabilities of becoming full (HMM)

- **Routing Plan – Dynamic IRP**

  Small instances were tested (18 bins, planning period of 7 days)

  - Develop other solution methods to solve larger instances (matheuristics, metaheuristics, …)

  Improve the integration between HMM and IRP model -> Stochastic IRP?

THANK YOU FOR YOUR ATTENTION!

WSMARTROUTE

http://wsmartroute.tecnico.ulisboa.pt/

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